

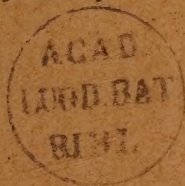
THE INFLUENCE OF NICKEL AND CARBON ON IRON.

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN THE
FACULTY OF PURE SCIENCE, COLUMBIA
UNIVERSITY, NEW YORK CITY.

BY

G. B. WATERHOUSE
(NEW YORK).

*Reprinted from the "Journal of the Iron and Steel Institute,"
No. II., for 1905.*



BY AUTHORITY OF THE COUNCIL.

LONDON:
PUBLISHED AT THE OFFICES OF THE INSTITUTE,
28, VICTORIA STREET, S.W.

1906.

BIOGRAPHICAL.

George Booker Waterhouse was born in Sheffield, England, May 25, 1883. After passing through the ordinary and higher school, he entered the Technical Department, University College, Sheffield, now Sheffield University. Here he obtained the associateship of the college in Metallurgy, together with the Mappin Medal. He has also obtained silver medals from the city and guilds of London Institute; first for the ordinary, and then for the honors grade, in iron and steel manufacture.

In 1901 he was awarded a probationary bursary by the Royal Commissioners for the Exhibition of 1851, followed by the full scholarship in 1902. With this he entered the Department of Metallurgy, Columbia University, taking post-graduate work. In 1904 he was awarded a President's University Scholarship, Columbia University, and in 1905 was assistant in the Department of Metallurgy, at the same time pursuing his studies for the degree of Doctor of Philosophy.

THE INFLUENCE OF NICKEL AND CARBON ON IRON.

THE INFLUENCE OF NICKEL AND CARBON ON IRON.*

BY G. B. WATERHOUSE (NEW YORK).

THE following paper is based on an investigation conducted in the metallurgical laboratory of the School of Mines of Columbia University in the City of New York.

The author has much pleasure in acknowledging the ready counsel and aid of Professor Howe, who has revised the paper critically, and of the members of his staff; and, above all, he has to thank Professor Bradley Stoughton, under whose immediate direction the work of investigation was carried out.

Thanks are also due to Dr. J. A. Mathews, of the Research Department of the Crucible Steel Company of America, for superintending the making of the steels; to Mr. Albert Ladd Colby, Assistant to the President of the International Nickel Company, for his gift of pure electrolytic nickel; and to Professor I. A. Woolson, of the Mechanical Engineering Department, Columbia University, for allowing the mechanical tests to be made in his laboratory.

OBJECT OF THE INVESTIGATION.

The object of the following research is to help in the study of the ternary alloys of iron, carbon, and another metal or metalloid, by considering a series of steels of constant nickel with varying carbon percentages. The other elements, which are present of necessity, were kept as low and constant as possible.

Historical.—The influence of carbon on iron has, up to the present, held the foremost place in research work relating to steel. This is natural, considering the great importance of the subject. The work of Professor J. O. Arnold¹ is especially valuable in this connection.† He experimented with fifty pound crucible ingots of great purity. The special importance of this classical research lies in the fact that it constitutes a

* Dissertation submitted in partial fulfilment of the requirements for the degree of Ph.D., Columbia University.

† The reference numbers in the text refer to the Bibliography given in the Appendix.

base line of knowledge, compared with which the influence of the other elements found in steel can be studied and estimated.

The properties of the binary alloys of many elements with iron have been studied in some detail, notably by Mr. R. A. Hadfield. There still remains, however, a wide field open for research in finding the effects of the different elements on pure iron and carbon steels. The remarks of an eminent writer in another branch of science may be directly applied²: "As yet this field has been barely scratched upon the surface; upon deeper cultivation a goodly crop may be secured."

The earliest experimenters with nickel were Faraday and Stodart, who, in 1820,³ in the laboratory of the Royal Institution, made small amounts of many alloys, using wrought-iron nails, and metals such as silver, gold, platinum, and nickel. Their two nickel alloys contained, by calculation, 3 and 10 per cent. of nickel respectively. The small laboratory ingots worked down well, and proved capable of taking a high polish, yielding promise of future usefulness for mirrors.

Probably the next work was that done by Sir Henry Bessemer in 1862.⁴ He melted metallic nickel and wrought iron containing much sulphur and phosphorus together in a crucible. The resulting ingot was badly red-short, and as Sir Henry was very busy at the time overcoming the prejudices against his new steel, the experiment was not followed up.

In 1887 Mr. Marbeau was working on the subject in France, and took out several patents. As a consequence a Glasgow company became interested, and commissioned Mr. James Riley to investigate the subject. After going to France and examining the new steels, he was so favourably impressed that, on his return, he ran twelve heats of nickel steel in a 10-ton acid open-hearth furnace. The composition of the resulting steels was very variable, the nickel rising from 1 per cent. to 50 per cent., the manganese being very high, and the carbon fairly high. All the steels forged well.

The results, when presented to the Iron and Steel Institute in 1889,⁵ aroused great interest. There was an animated discussion, during the course of which it transpired that Mr. James F. Hall, of Sheffield, had been quietly and successfully working on the subject for some time.

This paper, and the discussion attending it, directed the attention of the iron and steel world to the new material, and its manufacture was especially followed up in America. The reason for this may be mentioned briefly. In 1890 the United States Naval Bureau was endeavouring to find the best material to use as a protection for its battleships. Several continental firms supplied experimental armour plates, consisting of carbon steel, compound wrought iron and steel, and nickel steel. During October and November 1891 the famous armour-plate trials at Indian Head took place.⁶ Quoting from one of the reports: "Further light was thrown upon the question of the relative merits of the all steel and nickel steel armour, and any doubt which may have remained was finally set at rest. The nickel steel plates proved to be far superior to the Harveved steel plates, notwithstanding the advantages that it may have derived from the special treatment." As a consequence, the Naval Bureau decided that the new cruisers should be protected by nickel steel containing 3.25 per cent. nickel.

Although this provided the first and most important use for the new steel, it is constantly finding new applications, and has been very successfully employed for boiler and ship plates, shafting, forgings, hydraulic cylinders, and structural beams and shapes.

With higher percentages of nickel the alloys are less corrodible, and are now being employed for boiler tubes; and, on account of the low coefficient of expansion, for surveying instruments, chronometer springs, pendulums, and weights and measures. All these commercial steels contain a considerable quantity of manganese, masking the influence of the carbon and nickel.

Present Condition of our Knowledge.—Probably the largest amount of work on nickel steels has been done by Mr. L. Dumas, whose monograph appeared in the *Annales des Mines*.⁷ It is divided into the following sections:—

1. Steels with nickel alone, no chromium, and carbon and manganese very low.
2. Nickel steels with carbon, chromium, and manganese; subdivided into:—

- a. Nickel steels with carbon ;
- b. Nickel steels with chromium ;
- c. Nickel steels with manganese.

3. A rapid review of the properties of very high nickel alloys.

Mr. C. E. Guillaume has studied the alloys of iron and nickel with regard to their expansion with heat, and their magnetism, elasticity, density, and electrical resistance. The whole of his alloys, together with many others prepared at Imphy, making a total of a hundred and thirteen, were examined by Mr. Dumas.

In subdivision *a* of the second division, which deals with the question which we are studying, the properties of nineteen nickel steels with carbon are given. They are divided into six groups, in each of which the carbon varies, while the nickel is fairly constant. The first and second groups contain about 30 per cent. of nickel, and the percentage then drops to the sixth group with about 10 per cent.

This is the lowest percentage which he studied, and there are only two samples in the group, one containing 0·1 per cent. carbon, and the other 1·37 per cent. carbon and 2·71 per cent. manganese.

A table of mechanical tests of forgings has been issued by the Bethlehem Steel Company, which, as it shows the influence of nickel with the lower percentages of carbon, may be reproduced here. The steels were made by the open-hearth process, and so contain about 0·5 per cent. of manganese.

TABLE I.—*Nickel Steels made by the Bethlehem Steel Company.*

Carbon.		Nickel.		Elastic Limit per Square Inch.		Tenacity per Square Inch.		Elonga- tion per Cent.	Reduction of Area per Cent.
Per Cent.	Per Cent.	Tons.	Lbs.	Tons.	Lbs.				
0·2	...	12·50	28,000	24·80	55,000			34	60
0·2	3·50	21·40	48,000	37·90	85,000			26	55
0·3	...	16·50	37,000	33·50	75,000			30	50
0·3	3·50	26·80	60,000	42·40	95,000			22	48
0·4	...	19·20	43,000	37·90	85,000			25	45
0·4	3·50	32·20	72,000	49·20	110,000			18	40
0·5	...	21·40	48,000	42·40	95,000			21	40
0·5	3·50	37·90	85,000	55·80	125,000			13	32

There are also a great many results published showing the difference that the addition of about 3·4 per cent. nickel makes in the mechanical properties of a low carbon steel made by the open-hearth process. A large number may be found in the discussion attending the reading of Mr. Wiggin's paper,⁹ and in papers by D. H. Browne,⁸ and by F. L. Sperry,¹⁰ whilst others are found scattered through the various technical magazines.^{6, 11} By taking the tests given on steels of closely related composition and treatment, and taking averages, Table II. was arrived at. This shows the comparative properties of low carbon steel made in the acid open-hearth with and without nickel.

TABLE II.—*Comparison of Low Carbon Open-hearth Steels.*

Carbon.	Man- gane- se.	Nickel.	Elastic Limit per Square Inch.		Tenacity per Square Inch.		Elong. per Cent. on 8 Inches.	Reduction of Area per Cent.
Per Cent.	Per Cent.	Per Cent.	Tons.	Lbs.	Tons.	Lbs.		
0·25	0·58	...	16·1	36,064	28·69	64,260	26·63	58·20
0·24	0·66	3·43	25·6	57,344	39·09	87,561	23·20	54·40

Mr. F. L. Sperry also gives particulars in his paper¹⁰ of an interesting series of eight steels made in a small open-hearth furnace. The carbon rises from 0·16 to 0·91, but the nickel is by no means constant, varying from 2·05 to 4·93. Owing to adverse conditions it was found "impossible to make steel of a uniform grade, or show the degree to which a definite percentage of nickel in steel would be influenced by varying percentages of carbon, and *vice versa*."

From the averages given in Table II., representing the work of many experimenters, we see that in the case of mild open-hearth steels which have been thoroughly examined, the addition of about 3·4 per cent. nickel increases the tenacity from 30 to 50 per cent.; whilst the ductility is only lowered 10 to 20 per cent. As the carbon rises, the increase in tenacity due to the presence of nickel is not so great. Still in the highest sample of the Bethlehem Steel Company's table, containing

0·5 per cent. carbon, and 3·5 per cent. nickel, the tenacity is raised 31 per cent., whilst the ductility is lowered about 33 per cent.

An important point in connection with the tenacity is that the ratio of the elastic limit to the ultimate strength is greater than that of ordinary commercial steels. Mr. A. L. Colby gives the following figures based on his experience at Bethlehem on steel forgings:—

	Per Cent.
Mild steel ratio	46·40
Medium hard steel	46·20
Medium hard nickel steel	58·70

These steels were made by the acid open-hearth process, and contained about 0·5 per cent. of manganese.

The microscopy of nickel steels has not been extensively studied. In 1894 Professor Arnold¹² microscopically examined an alloy containing 1·51 per cent. of nickel, the other elements being very low. It showed ferrite in smaller crystals than usual. Dr. Mathews¹³ found the same result with his low carbon iron and nickel alloys. In 1898 Mr. Osmond¹⁴ investigated the series prepared by Mr. Hadfield.¹⁵ He divides the alloys into three groups, according to their nickel percentage, as follows:—

1. From 0·0 to 8·0 per cent. of nickel the structure is similar to that of the carbon steels, but with smaller crystals.
2. From 12·0 to 15·0 per cent. nickel the structure consists of rectilinear fibrous sheafs, parallel in three directions, showing the characteristics of quenched steels.
3. From 25 to 50 per cent. nickel the structure is purely that of white allotriomorphic crystals.

Dr. Léon Guillet has contributed some very important papers on this subject.¹⁶ His work was performed on three series of very pure steels, each consisting of nine samples. The carbons in these three series is respectively about 0·12 per cent., 0·25 per cent., and 0·8 per cent., and the nickel rises in each group from about 2·0 per cent. to 30·0 per cent. He has represented his results diagrammatically in the accompanying figure, of which a brief description may be given.

The co-ordinates represent carbon and nickel percentages. Considering a case with 0.5 per cent. carbon and increasing nickel will help to make it clear. With up to 7 per cent. nickel the steels are pearlitic, and similar to ordinary steels. Above 7.0 per cent. nickel a martensitic structure is seen, and with 9.0 per cent. nickel the whole field is martensitic. When the nickel has increased to 17 per cent. white polyhedra

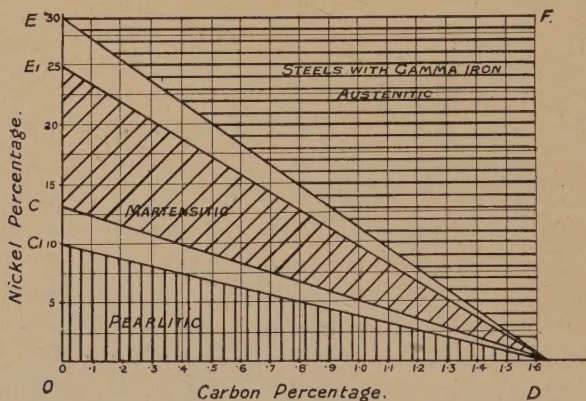


FIG. 1.

of austenite begin to appear, and increase in volume until, with 20.0 per cent. of nickel, they occupy the whole field.

By examining his three series the points were found where martensite began to show; where the whole field was martensite; and similarly with regard to the white polyhedra of austenite.

These points, when joined, divided the field into triangles as shown, because they converged to a point where the material contained 1.65 per cent. of carbon. The two small unshaded triangles are transition areas between the triangles that correspond to Mr. Osmond's three classes. Dr. Guillet says:—

"Micrographic study clearly shows that the constituents of these steels are:—

- "1. Ferrite, pearlite, and of course sorbite and troostite.
- "2. Martensite.
- "3. Acicular crystals, sometimes, with no apparent reason, white, and sometimes black.
- "4. White polyhedra."

The diagram has only been tested with steels containing up to about 0.8 per cent. carbon.

Some results have been obtained with regard to the recalcence of nickel steels. In the paper on "The Influence of Elements on Iron,"¹² Professor Arnold found that the alloy containing 1.51 per cent. nickel gave arrests in the heating curve at 702° C., 733° C., and 808° C.; and that, on cooling, points were found at 742° C. and 645° C. He observes that nickel somewhat lowers Ar1 on heating, distinctly on cooling. Ar2 is singularly constant throughout; while Ar3 is lowered to or below Ar2.

Mr. Osmond examined thermally the alloys of iron and nickel of Mr. Hadfield. He found that with increasing nickel the critical points were constantly lowered, until with 24.51 per cent. of nickel the recalcence was not complete at ordinary temperatures. Alloy E containing 3.82 per cent. nickel, 0.19 per cent. carbon, 0.65 per cent. manganese, and 0.20 per cent. silicon, gave critical points on heating at 680° C. and 740° C.; and on cooling at 645° C. to 635° C., and 565° C. to 550° C. Dr. Mathews, in his paper presented to the Iron and Steel Institute in 1902,¹³ had three alloys of iron with nickel ranging from 1.07 per cent. to 5.35 per cent. The one containing 3.37 per cent. nickel and 0.163 per cent. carbon gave tentative determinations of the critical points at 870° C., 710° C., and 630° C., which were the arrests observed in the cooling curve. In the present paper this steel was re-examined and gave the following points: On heating at 702° C. to 714° C., and at 754° C.; and on cooling at 702° C. to 690° C., and at 619° C.

EXPERIMENTAL METHODS AND LINE OF RESEARCH OF THIS PAPER.

The materials employed by the author in preparing the steels were puddled bar iron, known as muck bar; wood charcoal, and an especially pure sample of electrolytically deposited nickel. The nickel was melted in a crucible, thoroughly mixed, and shotted to get it in a form suitable for weighing. It was decided to make a series of nine ingots,

with the nickel constant at about 3·5 per cent. and the carbon rising from 0·40 per cent., which was the lowest possible, using graphite crucibles, to about 1·60 per cent.

The muck bar, as may be seen in the chemical section, compares very favourably with the best Swedish iron. 89·5 pounds of it were charged into the crucible together with the calculated amount of charcoal. The furnace was a Siemens regenerative one, gas fired. When clear melted 3·5 pounds of the shotted nickel were added. Before teeming 0·5 of an ounce of aluminium was thrown in, the steel poured into a second hot crucible to ensure mixing, and then into a 4½ inch square mould. When topped the ingots showed no sign of blowholes or piping, and the surface was good and smooth.

The fractures were so different from those of ordinary steel that they quite deceived the inspector, who usually grades the steel very accurately. After topping, the ingots were reheated, hammered down to 1½ square inch billets, and finally reheated and rolled to 1 inch diameter round bars.

An extremely interesting point was the entire absence of any difficulty due to a thick and clinging scale. This scale is mentioned by Mr. E. Windsor Richards in the discussion following the reading of Mr. Wiggin's paper. He considered it to be one of the great difficulties attending the use of nickel steel, which was then a new material, and in the case of plates it produced a rough surface. Mr. F. W. Paul, speaking in the same discussion, had experienced the same difficulty, especially with plates over ¾ inch thick. Mr. J. G. Eaton, of the United States Navy, had also noticed the same phenomenon, the rolling in of the scale producing a series of ridges on the under surface. The difficulty has not been met with much in America, owing, probably, to the high manganese contents of the steels. As will be shown later, the series of steels examined in this research are very low in manganese. It is interesting to find that a small amount of aluminium has taken the place of the manganese, and that without any special precautions the steels rolled perfectly.

The plan of research was to take the bars prepared in the above manner and to examine them thoroughly, first obtaining

their complete chemical analyses, and then testing them mechanically under several conditions of heat treatment. Micrographic analyses under these conditions were to be also made, and the heating and cooling curves determined. The results may be conveniently classified under the heads chemical, mechanical, microscopical, and pyrometric.

CHEMICAL.

On analysis the nickel gave the following figures:—

	Per Cent.
Nickel	99.47
Cobalt	trace
Silicon	0.015
Manganese	trace
Iron	0.437
Copper	0.025
Arsenic }	0.028
Antimony }	
Sulphur	trace
Oxygen (by difference).	0.025
Total	100.00

The only impurity in large amount is the iron, which is of no consequence.

The analysis of the muck bar is given in Table III.

TABLE III.

Mark of Steel.	Muck Bar.	K.	L.	M.	N.	P.	O.	Q.	R.	S.	T.
Carbon in ingot . . .	...	0.40	0.49	0.61	0.82	0.93	1.00	1.23	1.46	1.62	1.83
Total carbon in bar .	0.12	0.41	0.51	0.63	0.79	0.92	0.97	1.24	1.54	1.64	1.82
Nickel	...	3.79	3.79	3.76	3.81	3.79	3.75	3.81	3.82	3.82	3.79
Silicon	0.055	0.102	0.103	0.133	0.129	0.126	0.095	0.117	0.144	0.151	0.133
Manganese	trace	0.086	0.054	0.05	0.051	0.047	0.058	0.057	0.054	0.047	0.051
Sulphur	0.008	0.013	0.014	0.014	0.014	0.014	0.014	0.015	0.015	0.014	0.016
Phosphorus	0.007	0.007	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.009	0.009
Aluminium	...	0.01	0.01	0.009	0.01	0.009	0.011	0.009	0.01	0.01	0.01

Before the ingots were worked drillings were taken from them at a depth of 1 inch near to the top. The carbon was estimated, and the results which were obtained at the works at Syracuse are given in the first column of Table III. The

other results are those found by the author in the metallurgical laboratory, Columbia University, on drillings taken from three to five places in the rolled bars, and well mixed. They are arranged in order of ascending carbon. Through an error at the mill, O and P were mislettered, so that they do not come in alphabetical order.

It is gratifying to notice the low sulphur. In the case of a coke-fired furnace it would not have been lower than 0.025 to 0.030 per cent., even with the best coke, because the steels were in the furnace for an average of $4\frac{1}{2}$ hours.

The carbon in the upper members of the series existed in two forms, combined and graphitic. The percentages are given in Table IV.

For the definitions of the treatment the steel has undergone reference may be made to the mechanical section.

TABLE IV.

Number.	Rolled.		Submitted to Treatment A.		Submitted to Treatment B.	
	Combined Carbon.	Graphitic Carbon.	Combined Carbon.	Graphitic Carbon.	Combined Carbon.	Graphitic Carbon.
Q	1.24	...	1.24	...	1.24	...
R	1.48	0.04	1.21	0.31	0.50	1.02
S	1.13	0.51	0.93	0.71	0.21	1.43
T	1.02	0.80	0.91	0.91	...	..

The graphitic carbon of these steels corresponds to the temper carbon of Professor Ledebur,¹⁷ now known as temper graphite; it is insoluble in boiling hydrochloric or nitric acid. It is distinct from ordinary graphite because the microscope shows it to occur in an amorphous condition. According to Dr. Mathews there is slightly more in the $1\frac{1}{2}$ -inch square billets than in the rolled bars, so that it shows a tendency to re-combine with the iron when heated under oxidising conditions; and so meets Professor Ledebur's three requirements for temper carbon.

The carbon was carefully estimated in duplicate by dry combustion.

The temper graphite was estimated by digesting three grams of the drillings with 1.20 specific gravity nitric acid at a temperature of 90° C. When the steel was dissolved, the residue was filtered, washed, dried, and ignited as before.

The nickel was estimated volumetrically by means of cyanide of potassium. The iron was separated by means of the separation method given in Brearley and Ibbotson's "Analysis of Steelworks Materials."¹⁸

The following table shows how these results compare with those obtained electrolytically by the chief chemist of the International Nickel Company.

TABLE V.

Method.	K.	L.	M.	N.	P.	O.	Q.	R.	S.	T.
Electrolytic	3.82	3.83	3.78	3.86	3.81	3.78	3.86	3.90	3.90	3.85
Volumetric	3.79	3.79	3.76	3.81	3.79	3.75	3.81	3.82	3.92	3.79

The remaining elements were estimated by the methods recommended in Professor Arnold's "Steelworks Analysis."¹⁹

MECHANICAL.

Definitions: Treatment A.—Pieces of each bar, 12 inches long, were placed in a gas-fired muffle, and raised to 1000° C. They occupied 1 hour 25 minutes in reaching this temperature. For 25 minutes they were maintained at this heat, then removed and cooled in air. The object of this procedure was to re-crystallise the steels, and to remove any distortion or strain produced during the rolling. The treatment corresponds to the "normalising" used by Professor Arnold in his researches, so that the results given in this paper are comparable with his.

Treatment B.—The bars were packed in a wrought-iron tube, placed in an annealing furnace at 500° C., and brought to a temperature of 870° C. to 880° C. in 5½ hours. They were kept at this temperature for three hours, then the tube was withdrawn and cooled in a pit with many other filled pipes, and the whole covered with ashes. In 24 hours the pipes were emptied, the steel being at about 150° C.

For tensile testing the bars were turned down to a diameter of 0.564 inches, giving an area of 0.25 square inch. Through the kindness of Professor I. A. Woolson, of the Department of Mechanical Engineering, Columbia University, the testing

DIAGRAM OF MECHANICAL TESTS.

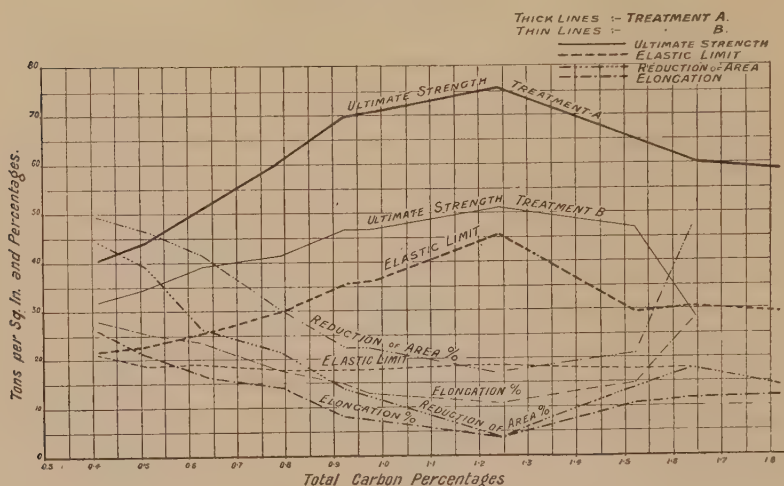


FIG. 2.

was carried out in his laboratory. The results are given in Table VI., and also diagrammatically in Fig. 2.

MICROSCOPICAL.

Transverse sections have been made of the bars in the rolled and other conditions, and also of K, P, and Q, which contained respectively 0.41, 0.92, and 1.24 per cent. carbon after they had been through the following treatment. They were placed in a Sauveur platinum resistance furnace, which was then luted up. In 10 hours they had reached 800° C., and in 9 more hours they were at 1080° C. The voltage was then lowered, and in 24 hours from the commencement of the operation the furnace was at 680° C. For 22 hours the temperature very slowly fell to 650° C., and then the current was cut off. The steels were removed after another

TABLE VI.

No.	Ni.	C. C.	Gr. C.	Elastic Limit per Square Inch.		Ultimate Strength per Square Inch.		Elong. per Cent. in 2 Inches.	Reduction of Area per Cent.	Fracture.
				Tons.	Lbs.	Tons.	Lbs.			
KA*	3.79	0.41	...	21.68	48,563	40.28	90,246	26.0	44.75	Light grey granular; silky edges; half cup and cone.
KB*	3.79	0.41	...	20.74	46,469	31.94	71,559	28.0	49.4	Light grey granular; silky edges; half cup and cone.
LA	3.79	0.51	...	22.52	50,469	44.24	99,109	21.0	39.05	Light grey granular; silky edges; half cup and cone.
LB	3.79	0.51	...	18.66	41,812	34.75	77,861	25.5	46.78	Light grey granular; silky edges; half cup and cone.
MA	3.76	0.63	...	25.01	56,041	51.52	115,421	16.5	26.27	Finely crystalline, and serrated edges.
MB	3.76	0.63	...	18.83	42,209	39.0	87,360	23.5	41.45	Grey granular; tendency towards cup and cone.
NA	3.81	0.79	...	29.84	66,850	60.55	135,194	14.0	21.27	Finely crystalline, with serrated edges.
NB	3.81	0.79	...	17.79	39,875	41.21	92,313	17.5	30.11	Grey granular; crystalline near the edge.
PA	3.79	0.92	...	35.04	75,000	69.42	155,502	8.0	14.08	Crystalline; radial furrows; serrated edges.
PB	3.79	0.92	...	17.71	39,688	46.45	104,068	15.0	22.61	Fine crystalline; serrated edges.
OA	3.75	0.97	...	35.76	80,120	70.01	156,827	7.5	8.39	Fine crystalline; even surface.
OB	3.75	0.97	...	17.87	41,035	46.46	103,187	13.0	22.43	Crystalline, with granular centre.
QA	3.81	1.24	...	45.44	102,030	75.31	168,697	3.50	3.20	Fine crystalline; very level fracture.
QB	3.81	1.24	...	18.38	41,186	50.74	113,673	11.0	17.21	Rather coarsely crystalline; little glistening flakes.
RA	3.82	1.21	0.31	29.25	65,530	65.01	145,642	10.5	13.9	Crystalline, but grey in colour; serrated edges.
RB	3.82	0.50	1.02	17.34	38,847	46.84	104,934	14.5	20.96	Crystalline, but grey in colour; serrated edges.
SA	3.92	0.93	0.71	30.18	67,605	60.59	135,734	11.5	17.86	Very dark grey granular; uneven surface.
SB	3.92	0.21	1.43	17.81	39,910	29.34	65,732	27.5	46.89	Very dark grey fracture; almost cup and cone.
TA	3.79	0.91	0.91	29.66	66,440	58.76	131,612	12.0	13.92	Very dark grey granular; edges slightly silky, and deeply serrated.

* "A" after the number of a steel signifies subjected to treatment A, while "B" signifies subjected to treatment B. (See page 387.)

22 hours, being then at 100° C. The furnace temperature was controlled by a Le Chatelier thermo-electric pyrometer.

The sections were rubbed down on six emery papers of successively finer surface, and finally polished with wet rouge. In most cases they were then etched with a 5 per cent. solution of picric acid in alcohol, and examined. Several were photographed unetched. In photographing, arc light illumination was used in connection with a yellow screen and orthochromatic plates. The results of the photomicrographic examination are tabulated on pp. 392 and 393.

Separation and Analysis of Carbide.—On the advice of Professor Stoughton the composition of the carbide of these nickel steels was determined, in order to ascertain whether the nickel replaces the iron atom for atom.

A sample of O in the condition after treatment B was taken for electrolysis, the method being that recommended by Arnold and Read.²⁰ By means of a resistance in the circuit the current was kept at one ampere for 94 hours, when the piece was removed. The carbide was mostly attached to the bar. When removed it appeared as a grey sludge with a silvery sheen. The sample weighed originally 178.265 grams, and lost 31.23 grams by the operation. On analysis the figures given in Table VII. were obtained.

TABLE VII.—*Analyses of Separated Carbides.*

	Carbide from OB.	Carbide from QA.
Carbon per cent. . . .	6.52	10.07
Nickel „	1.86	2.79
Iron „	91.71	71.61
Silicon „	0.05	0.41
Total	100.14	84.88

The same treatment was tried on a sample of Q in the condition after treatment A. During the electrolysis there was a continuous liberation of gases from the piece, some of which were undoubtedly hydrocarbons, judging from their odour. The carbide appeared as a dark-coloured amorphous powder, and had the analysis given in Table VII. The result will be discussed under a later heading.

PYROMETRIC.

The temperatures in this section were all obtained with a Le Chatelier thermo-couple consisting of wires of platinum and platinum alloyed with 10 per cent. iridium. A delicate dead-beat mirror-galvanometer made by Carpenter was used, and the deflections observed by means of a scale and lamp in the usual manner.

For calibration the boiling points of water (100° C.), naphthalene (218° C.), and sulphur (448° C.); and the freezing points of tin (232° C.), zinc (420° C.), aluminium (655° C.), and copper (1084° C.) were used, plotting temperatures and the galvanometer readings as co-ordinates.

The critical points were determined by taking pieces of the steels $1\frac{1}{4}$ inch long, and drilling a $\frac{5}{16}$ -inch hole $\frac{5}{8}$ of an inch deep. Into this a fireclay couple cover just fitted, bringing the thermo-junction in the centre of the piece. The arrangement is shown in Fig. 3. The piece was packed in well-ignited asbestos in a crucible, and the heatings carried out in a small Fletcher furnace.

The results obtained on heating and cooling are given in Table VIII.

TABLE VIII.—*Recalcescence Results.*

Mark.	C. C. per Cent.	Gr. per Cent.	Ni. per Cent.	Heating.		Cooling.	
				Ac2.3. Degrees C.	Ac1. Degrees C.	Ar3.2. Degrees C.	Ar1. Degrees C.
KA	0.41	...	3.79	744	704-714	653-638	608-598
LA	0.51	...	3.79	734	699-714	640	615-605
MA	0.63	...	3.76	...	702-717	...	610-600
NA	0.79	...	3.81	...	703-718	...	612-602
PA	0.92	...	3.79	...	691-706	...	612-602
OA	0.97	...	3.75	...	701-716	...	612-602
QA	1.24	...	3.81	...	688-698	...	620-610
RA	1.21	0.31	3.82	...	683-693	...	621-611
SA	0.93	0.71	3.82	...	700-710	...	623-613
TA	0.91	0.91	3.79	...	696-711	...	627-606
RB	0.50	1.02	3.82	...	696-711	...	615-605
SB	0.21	1.43	3.82	727	697-712	...	626-606

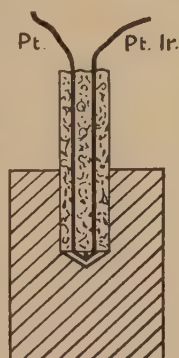


FIG. 3.—Arrangement of Recalcescence Piece.

Mark.	Combined Carbon per Cent.	Graphite per Cent.	Condition.	Microstructure.
KR	0·41	...	Rolled.	Ferrite with pearlite, the former in slightly greater amount. Small interlocking structure. See Micrograph 1.
KA	0·41	...	Treatment A.	Similar to KR, somewhat coarser structure. Pearlite laminated. See Micrographs 7 and 8.
KB	0·41	...	Treatment B.	Complete segregation of pearlite into ferrite and cementite, which is in isolated masses. Fine structure. See Micrograph 19.
K	0·41	...	Special treatment.	Similar to KB, but the structure much coarser; segregation not complete. See Micrograph 25.
LR	0·51	...	Rolled.	Matrix of granular pearlite with ferrite. Fine interlocking structure. See Micrograph 2.
LA	0·51	...	Treatment A.	Similar to LR, but with a much coarser structure. See Micrograph 9.
LB	0·51	...	Treatment B.	Similar to KB, but with a little more cementite. Very fine structure.
MR	0·63	...	Rolled.	Matrix of pearlite with ferrite; slightly coarser than LR. See Micrograph 3.
MA	0·63	...	Treatment A.	Much coarser than MR, but the same constituents. See Micrograph 10.
MB	0·63	...	Treatment B.	Very fine structure; ferrite and separated cementite in meshes.
NR	0·79	...	Rolled.	Pearlite, with only a small amount of ferrite. See Micrograph 4.
NA	0·79	...	Treatment A.	Matrix of pearlite; coarser structure than NR, and with less free ferrite. See Micrograph 11.
NB	0·79	...	Treatment B.	Very small structure of ferrite and cementite. See Micrograph 20.
PR	0·92	...	Rolled.	Granular pearlite.
PA	0·92	...	Treatment A.	Granular or slightly laminated pearlite.
PB	0·92	...	Treatment B.	Similar to NB, but with more cementite.
P	0·92	...	Special treatment.	Laminated pearlite, with excess of cementite in thin meshes. See Micrograph 26.

Mark.	Combined Carbon per Cent.	Graphite per Cent.	Condition.	Microstructure.
OR	0.97	...	Rolled.	Similar to PR.
OA	0.97	...	Treatment A.	Granular or slightly laminated pearlite, with a very few thin meshes of cementite.
OB	0.97	...	Treatment B.	Finer structure than NB, and similar to it, but having more cementite. See Micrograph 21.
QR	1.24	...	Rolled.	Matrix of granular pearlite, with thin cell walls of cementite, some of which is inside the cells. Fine interlocking structure. See Micrograph 5.
QA	1.42	...	Treatment A.	Similar to QR; larger structure and slightly thicker cell walls. See Micrograph 12.
QB	1.24	...	Treatment B.	Granular pearlite matrix, with thick meshes of cementite. See Micrograph 22.
Q	1.24	...	Special treatment.	Matrix of laminated pearlite, with thick cell walls of cementite, some also being inside the cells. See Micrograph 27.
RR	1.48	0.04	Rolled.	Similar to Q R.
RA	1.21	0.31	Treatment A.	The temper graphite shows in small rounded masses in the polished section. When etched it is similar to QA, but with larger crystals of pearlite, which is mainly of a granular character, as shown by Micrograph 14. See also Micrographs 13 and 15.
RB	0.50	1.02	Treatment B.	Temper graphite very abundant in the polished section. The matrix is of ferrite and separated cementite. See Micrograph 23.
SR	1.13	0.51	Rolled.	When polished it shows globular masses of temper graphite; in the etched section granular pearlite and excess of cementite.
SA	0.93	0.71	Treatment A.	Similar to RA, but shows no free carbide in the etched section. The temper graphite is surrounded by a thin layer of ferrite. See Micrographs 16 and 17.
SB	0.21	1.43	Treatment B.	Similar to RB, but with more temper graphite and less cementite in the matrix, which is nearly all ferrite. See Micrograph 24.
TA	0.91	0.91	Treatment B.	Similar to SA. See Micrograph 18.

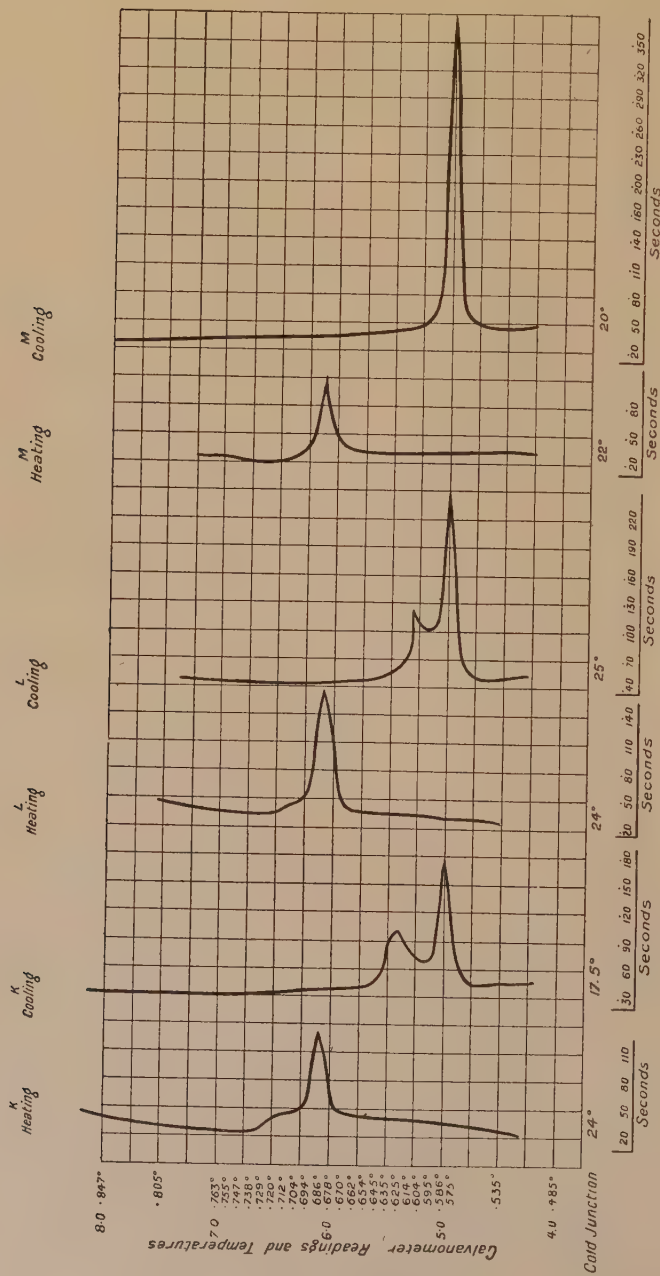


FIG. 4.

The heating and cooling curves of the first three members of the series are given in Fig. 4. They, especially that of M, are typical of the curves of the whole series.

On the advice of Professor Howe, Fig. 5 was prepared, which shows the relation of the critical points in cooling of these

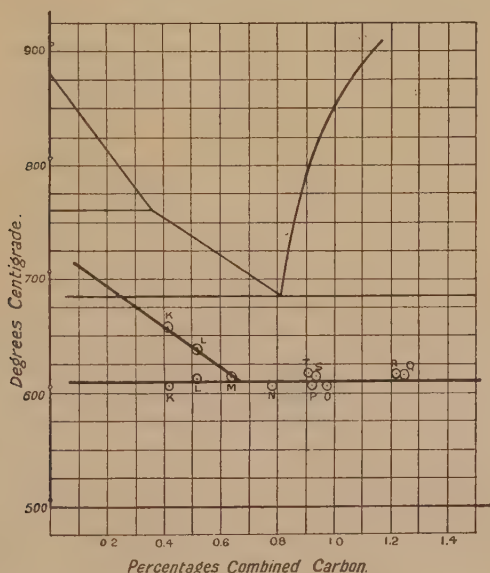


FIG. 5.

steels containing about 3.80 per cent. nickel, to those of the pure carbon steels of the Roberts-Austen diagram.

Comparison of the Critical Points with the Lower Part of Roberts-Austen's Diagram.

Consideration of Results.—Examining the table of the mechanical tests, and its accompanying diagram, it is seen that the action of carbon and nickel on iron is very similar to that of carbon alone. In the steels after treatment A, the tenacity, as shown by the elastic limit and ultimate strength, rises to a maximum with about 1·20 per cent. carbon. Above this amount the tenacity drops in part, because some of the carbon is in the graphitic form.

The effect of the nickel is clearly shown by the great tenacity possessed by these steels as compared with carbon steel. To illustrate this the tests given by two similarly treated steels of Professor Arnold's series may be given.

TABLE IX.—*Comparison with Carbon Steels.*

Carbon.	Nickel.	Elastic Limit.		Ultimate Strength.		Elastic Ratio.	Elongation per Cent. on 2 Inches	Reduction of Area per Cent.
		Tons.	Lbs.	Tons.	Lbs.			
0.38	...	17.95	40,208	29.94	67,055	60.2	34.5	56.3
0.41	3.79	21.68	48,563	40.28	90,246	53.7	26.0	44.7
1.20	...	35.72	80,012	61.65	138,096	57.8	8.0	7.8
1.24	3.81	45.44	102,030	75.31	168,697	60.3	3.5	3.5

The elastic ratio, or the ratio of the elastic limit to the ultimate strength, is not greatly raised by the addition of the nickel, and, in the lowest member of the series, is slightly below that obtained from the carbon series. There is no doubt that in commercial nickel steels the elastic ratio is decidedly raised, which may be due to the large amount of manganese that they contain.

Corresponding to the increase in tenacity with the rise in carbon, there is a decrease in the ductility as shown by the elongation and the reduction of area. At about 1.20 per cent. carbon the ductility reaches a minimum, and then rises as the total carbon increases, which increase is accompanied by the separation of graphitic carbon.

The tensile properties are not greatly different from those of the pure carbon steels, and the influence of the nickel has been to increase the tenacity without lowering the ductility to any large extent.

The weakening effect of the separated temper graphite is well shown by the steels QA and RA, the tests of which are given in Table VI. They contain respectively 1.24 and 1.21 per cent. of combined carbon.

The influence of treatment B has been very marked, as may be seen in Fig. 2. The ultimate strength has been greatly lowered. It steadily rises with the increase in carbon

until the latter is about 0.9 per cent., then rises slowly, attaining a maximum at about 1.2 per cent. The separation of the graphitic carbon is marked by a drop in the curve.

The elastic limit of the steels after treatment B is singularly uniform. It was determined in all cases by an extensometer, which, on account of its superior sensitiveness, gave its indications before the drop of the beam, to which, however, it closely corresponded. This interesting point will be referred to later. The ductility of the steel has been increased by the treatment B. It does not greatly decrease after the carbon has reached 0.90 per cent., and shows a rapid increase with the appearance of the graphitic carbon.

In the case of Mr. Hadfield's nickel iron alloys annealing did not have much effect, and he says: "The annealed cast bending bars, forged bending bars, and forged tensile bars show very little difference to the unannealed specimens, apparently showing that the annealing is of very little if any benefit." He expresses the wonder whether this would hold good with high carbon nickel steels, a question answered by these results in the negative.

The microscopical section shows that these steels belong to the first class of Osmond, and the pearlitic of Guillet, which is natural, because they lie wholly within the pearlitic area of Diagram I. The constituents are those of carbon steels, namely, pearlite with ferrite as the excess substance in hypoeutectoid or unsaturated, and cementite as the excess in the hyper-eutectoid or supersaturated steels. Graphite is also present. In the case of the rolled steels and those given treatment A, the free ferrite diminishes with increasing carbon, until P and O, containing 0.92 and 0.97 per cent. of carbon respectively consist entirely of pearlite. Above this percentage cementite is found. In the steels which have been given treatment A the pearlite is of a sorbitic structure. In the higher members of the series the separated carbon has so lowered the percentage of combined carbon that the structure is mainly pearlite. The separated carbon is in small globules in the interior of the pearlite, and is surrounded by a thin layer of ferrite.

The annealing given in treatment B has had such an effect

that the pearlite has separated into its constituents ferrite and cementite, and graphitic carbon is present in the higher members. In sample OB, containing 0·97 per cent. carbon, the carbide contains 1·86 per cent. nickel, and the ferrite has 1·89 per cent. in solid solution. It would appear that the uniform elastic limit of these steels, and the fact that they are all chiefly ferrite and cementite, have a direct bearing on each other. Three specially annealed steels are particularly interesting. The lowest carbon steel has separated into ferrite and cementite; the one with 0·92 per cent. carbon has well-developed pearlite with meshes of cementite, showing that this composition is above the eutectoid ratio; while the highest member, with 1·24 per cent. carbon, has a large excess of cementite.

In the steels given treatment B the cementite has the following composition:—

Carbon, per cent.	.	.	.	.	.	6·25 ÷ 12 = 0·54
Nickel	„	.	.	.	.	1·86 ÷ 55 = 0·034
Iron	„	.	.	.	.	91·71 ÷ 56 = 1·63

The percentages divided by the atomic weights give the ratios in the last column. That of the carbon to the nickel and iron is 0·54 : 1·664, which equals 1 : 3·08, so that the formula of the cementite is $\text{Fe}(\text{Ni})_{3\cdot08}\text{C}$, or, writing it simply, $\text{Fe}(\text{Ni})_3\text{C}$.

In the steels which have been given treatment A the finely divided, almost emulsified, cementite of the sorbitic pearlite suffers decomposition under the method employed for its separation, a moderate amount of hydrocarbons being given off, and free carbon also being produced. This makes it impossible to say what the analysis of the carbide is in the rolled steels and those given treatment A.

The results of the recalescence experiments show that the Ar1 point has been lowered 20° C. for each 1 per cent. of nickel; and that the eutectoid ratio has been lowered by the nickel to about 0·70 per cent. carbon. This receives support from the three micrographs, 25, 26, and 27; particularly 26, where the amount of free cementite shows the steel to possess more than the eutectoid amount of carbon. It is only in the steels that have been given the special treatment in the

electric furnace that the eutectoid ratio appears to be about 0·70 per cent. In the rolled steels, and those subjected to treatment A, it appears to be about 0·95 per cent., while treatment B was so drastic that the pearlite was broken up into its constituents, and time allowed for them to segregate.

CONCLUSIONS.

The following conclusions may be drawn from the results :—

1. Nickel decidedly raises the tenacity without materially lowering the ductility. The elastic ratio, in pure nickel-carbon steels, is only slightly greater than that of carbon steels.

2. Annealing has a marked influence ; it lowers the tenacity without greatly raising the ductility.

3. The constituents of steels with low percentage nickel in the unquenched state are : ferrite, pearlite, cementite, and graphitic carbon.

4. The pearlite of these steels shows a great readiness to segregate into its constituents : ferrite and cementite.

5. In this condition the cementite has the formula $\text{Fe}(\text{Ni})_3\text{C}$.

6. The eutectoid ratio in these steels appears to lie at about 0·70 per cent. carbon, but in the rolled steels no free cementite shows until the carbon reaches about 0·95 per cent.

7. Nickel lowers the transformation points Ar_3 , Ar_2 , and Ar_1 about 20° for every 1 per cent. of nickel.

8. The cementite of these steels is very liable to precipitate its carbon as “temper graphite.”

The paper is accompanied by five diagrams, from which the figures in the text have been prepared, and by twenty-seven photomicrographs, which were exhibited at the meeting and can be consulted in the Institute library.

BIBLIOGRAPHY.

1. ARNOLD, J. O. "The Influence of Carbon on Iron." *Minutes of Proceedings of the Institution of Civil Engineers*, vol. cxxiii. p. 127.
2. CLARKE, F. W. "The Constitution of the Silicates." *United States Geological Survey*, Bulletin 125.
3. STODART, J., and FARADAY, M. "Experiments on Alloys of Steel, made with a View to its Improvement." *Quarterly Journal of Science*, 1820, vol. ix. p. 319; vol. xiv. p. 377.
4. Discussion on Number 9.
5. RILEY, J. "Nickel and Steel Alloys." *Journal of the Iron and Steel Institute*, 1889, No. I. p. 45.
6. "Harveyised Nickel Steel." *Iron Age*, 1892, vol. xlix. p. 509.
7. DUMAS, L. "Recherches sur les aciers au nickel à hautes teneurs." *Annales des Mines*, 1902, vol. i. p. 357.
8. BROWNE, D. H. "Nickel Steel: a Synopsis of Experiment and Opinion." *Transactions of the American Institute of Mining Engineers*, 1899, vol. xxix. p. 569.
9. WIGGIN, H. A. "Nickel Steel, and its Special Advantages over Ordinary Steel." *Journal of the Iron and Steel Institute*, 1895, No. II. p. 164.
10. SPERRY, F. L. "Nickel and Nickel Steel." *Transactions of the American Institute of Mining Engineers*, 1895, vol. xxv. p. 51.
11. HARRINGTON, T. "Nickel Steel Experiments." *Iron*, Oct. 2, 1891, vol. xxxviii. p. 293.
 MERCADIER, E. "Coefficient of Elasticity of Nickel Steel." *Iron*, March 25, 1892, vol. xxxix. p. 270.
 PORTER, H. F. J. "Nickel Steel." *Cassier's Magazine*, 1902, vol. xxii. p. 480.
12. ARNOLD, J. O. "The Influence of Elements on Iron." *Journal of the Iron and Steel Institute*, 1894, No. I. p. 107.
13. MATHEWS, J. A. "A Comparative Study of Some Low Carbon Steel Alloys." *Journal of the Iron and Steel Institute*, 1902, No. I. p. 182.
14. OSMOND, F. "On the Microstructure of Alloys of Iron and Nickel." *Comptes Rendus*, 1898, vol. xciii. p. 1352.

15. HADFIELD, R. A. "Alloys of Iron and Nickel." *Minutes of Proceedings of the Institution of Civil Engineers*, 1899, vol. cxxxviii. pp. 1-124.
16. GUILLET, LÉON. "Metallography of Nickel Steel." *Bulletin de la Société d'Encouragement*, May 1903, p. 658.
 "Nouvelles Recherches sur les aciers au Nickel." *Génie Civil*, June 1903, vol. xliii. p. 134.
17. LEDEBUR, A. "Modifications of Carbon in Iron." *Journal of the Iron and Steel Institute*, 1893, No. II. p. 53.
18. BREARLEY, H., and IBBOTSON, F. "The Analysis of Steelworks Materials." London, 1902.
19. ARNOLD, J. O. "Steelworks Analysis." London, 1895.
20. ARNOLD, J. O., and READ, A. A. "Chemical Relations of Carbon and Iron." *Journal of the Chemical Society*, vol. lxxv. p. 788.

CORRESPONDENCE.

Dr. L. GUILLET (Paris) wrote that he was pleased to find that Mr. Waterhouse had arrived at practically the same conclusions as himself respecting the constitution of nickel steels containing less than 1.65 per cent. of carbon. At the same time he found himself in total disagreement with the author of the paper as to the following point. Mr. Waterhouse held that the formula of the cementite present in nickel steel was FeNi_3C ; he therefore appeared to believe that the nickel was in the state of carbide. The accuracy observed in Mr. Waterhouse's experiments on the subject did not appear sufficiently great to justify that conclusion, which was absolutely opposed to all the investigations which had been made on that point up to the present, and notably to those of Messrs. Carnot and Goutal, and those of Professor Le Chatelier. It should be recognised, speaking generally, that chemical analysis usually led to the finding of what it was desired to find, and that the conclusions to which it led should be confirmed by other means. At the commencement of his studies upon alloys he had himself succeeded, as he supposed, in isolating a large number of alloys of aluminium and of other metals, yet at the present time he was far from feeling so sure of his results, now that he had carried them further. Chemical analysis might supplement other methods for the investigation of the theory of alloys, such as micrography, transformation point determinations, electrical resistance, &c., but he believed that it was well, in all cases, to suspect results arrived at by its aid alone. He could not share the view which Mr. Waterhouse had adopted as the conclusion of his investigations, that the cementite of nickel steels possessed the formula which Mr. Waterhouse had ascribed to it, viz. FeNi_3C .

Dr. J. A. MATHEWS (Syracuse) wrote that he had been much interested in the results of Mr. Waterhouse upon the series of constant-nickel-variable-carbon alloys, and, together with Mr. J. H. Morecroft, electrical engineer, had made other tests, the

results of which might be of interest in supplementing or confirming the work of Mr. Waterhouse. If at some points their results differed, it would prevent conclusions being drawn from results that had failed of verification when the tests upon which they were based were repeated under slightly different conditions by other experimenters. The question of the separation of temper carbon in the alloys of highest carbon contents had received some attention in their work. The following were their analyses for temper carbon in the samples Q, R, S, and T:—

	Total Carbon in Ingot.	Temper Carbon in Billets.	Temper Carbon in Bars.	Temper Carbon in Annealed Bars.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Q. . . .	1·24	0·00	0·00	0·00
R. . . .	1·48	0·47	0·04	1·05
S. . . .	1·66	0·57	0·51	1·50
T. . . .	1·83	0·83	0·80	1·73

There would be seen here a tendency for the temper carbon to go back into combination in the rolled bar. That might seem somewhat surprising when it was reflected that the rolling and finishing were doubtless done at a much lower heat than the cogging. It would seem that that consideration was more than offset by the more rapid cooling in the case of 1 inch rounds as compared with $1\frac{1}{2}$ inch billets. The strength of the tendency to recombine decreased as the total carbon and total temper carbon increased. Comparing the natural and annealed bars, it appeared that the higher the carbon the more perfectly it separated out on annealing. In the case of the sample T, they had performed the old Metcalf experiment of hardening both annealed and unannealed pieces which had been deeply notched at intervals of 1 inch. There were seven segments in all, and the first segment was brought to a welding heat, while the heat on the seventh segment was a low hardening heat. After quenching the bars in cold brine they were fractured, and the temper carbon determined in the various segments. In the first segment there was still left a trace of temper carbon in the unannealed specimen, and a stronger trace in the previously annealed bar. The graphite progressively

increased further back on the bars, but at the sixth segment it amounted to only 0·30 and 0·23 per cent. respectively in the annealed and unannealed bars. The fracture at the seventh segment was decidedly dark, due to temper carbon in the annealed bar, and just appreciably off colour in the bar that had had no annealing prior to hardening. The test showed that the temper carbon readily passed into solution above A_{r1} , and probably a long time at a low heat or a short time at a high heat would effect complete solution. The physical properties noted on T, annealed and unannealed, were as follows:—

	Temper Carbon.	Elastic Limit.	Tensile Strength.	Elongation.	Reduction.
	Per Cent.	lbs. per sq. in.	lbs. per sq. in.	Per Cent.	Per Cent.
T, unannealed	0·80	86,500	143,000	8·4	15
T, annealed	1·73	40,000	58,500	33·0	52

The elongation was measured on 2 inches, and the reduction on a $\frac{1}{2}$ inch diameter. The hardness, by Brinell's test, was decreased from 271 to 131 by annealing, while the magnetic induction (B) at $H = 100$ was greatly increased, and the coercive force reduced from 18·8 to 4·8, the hysteresis in the annealed bar being just one-third of what it was in the unannealed condition. Comparing the electrical resistance of those steels with that of plain carbon steels of equal purity, it appeared that the addition of about 3·85 per cent. nickel raised the specific electrical resistance about 7·5 microhms per cubic centimetre in the annealed condition for all percentages of combined carbon. In the hardened state the increase in resistance was greater, and varied from 12 to 17 microhms per cubic centimetre. The electrical resistance of the annealed steel differed but little from that of the unannealed bars, excepting in the event of temper carbon being produced. 3·85 per cent. nickel was almost without effect in increasing the coercive force of the annealed bars as compared with similar carbon steels, annealed, but raised it considerably in the unannealed and hardened state. He had found that in certain classes of steels the magnetic hardness and physical hardness were closely related, and in some

cases seemed to be directly proportional. In the present series of steels they found by the Brinell test that nickel in the amount shown, annealed, either did not increase or slightly decreased the physical hardness. Comparing the samples K and R, containing nearly the same amount of combined carbon, he found that they had nearly the same coercive force and specific resistance, but R showed a lower hysteresis than K, and also lower tensile strength, elongation, and reduction. The induction of sample K showed it to be the more permeable however, but the difference was not great, and the general shape of the hysteresis loops was the same. In the unannealed and annealed steels free from temper carbon the hysteresis loss in ergs per cycle seemed to reach a maximum at sample Q. The elastic limit and tensile strength also increased directly with the carbon up to Q in his tests, and the elongation and reduction decreased to Q—the results of the higher carbons being omitted because of the temper carbon they contained. The coercive force was in all cases reduced by annealing, but the retentivity was often increased. The maximum induction for $H = 100$ was in some cases higher in the unannealed than in the annealed condition. That was not surprising when it was recalled that all bars had the same annealing, which might have been particularly good for some compositions and particularly bad for others. For $H = 25$ to 30 the induction was increased by annealing in every case, excepting sample O, in which it was greatly reduced. The hysteresis loss in ergs per cycle was determined in six of the specimens by Mr. Morecroft as follows:—

	Unannealed.	Annealed.	Reduction by Annealing.
			Per Cent.
K . . .	44,000	32,200	27·5
M . . .	59,600	34,100	42·8
O . . .	64,900	45,200	30·4
Q . . .	65,700	47,000	28·5
R . . .	64,000	25,700	60·0
T . . .	64,200	21,200	67·0

Crushing tests were made upon cylinders 1 inch in diameter and 2 inches high, carefully faced off at both

ends. At the maximum pressure of the machine—200,000 lbs.—all the pieces failed ultimately by bending, with the exception of R, unannealed. All the pieces stood at least 20 per cent. decrease in length before bending, and in Fig. 6 was shown the load necessary to produce 5 and 10 per cent.

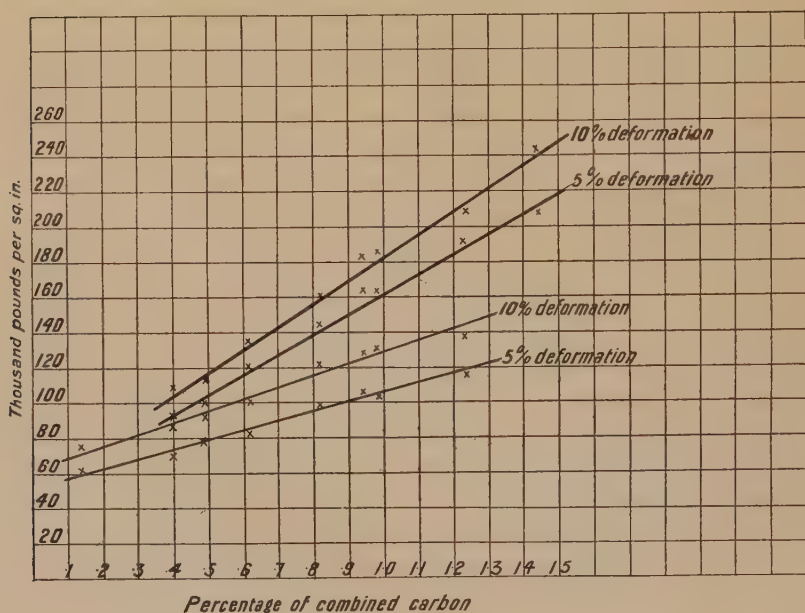


FIG. 6.

reduction in length in both the annealed and unannealed bars. Those were plotted with the load as one co-ordinate, and the combined carbon as the other. The result was practically a straight line in all cases, and it was interesting to note the inertness of temper carbon in the annealed specimens.

Mr. WATERHOUSE, in reply, expressed his pleasure at finding that Dr. Guillet's results on nickel steels were confirmed. With regard to the determination of the composition of the carbide of nickel steels, the procedure followed was the well-known method of Arnold and Read, giving the results obtained on pp. 390 and 398. It should be noticed that it was only in

the slowly cooled steels, where there had been ample time for the constituents to separate, that the carbide had the composition $\text{Fe}(\text{Ni})_3\text{C}$. In the case of the other steels, in the words of the text, the method adopted made it "impossible to say what the analysis of the carbide is in the rolled steels, and in those given treatment A."

The contribution by Dr. Mathews was very valuable, as it rendered more complete the tests on this series of steels. The terms unannealed referred to the bars in the rolled condition, and annealed to treatment B. With very slight variations his results confirmed those of the paper. It was interesting to note that although sample 2, with 1.24 per cent. of carbon, 3.81 per cent. of nickel, was far above the saturation point, no temper graphite separated out under the different heat treatment. Mr. Morecraft's tests on the hysteresis loss in ergs per cycle showed that in that case also, as in that of the mechanical tests, there was a bend in the curve at 1.24 per cent. of carbon.

